

Use of Laboratory Triaxial Creep Data
and Finite Element Analysis to Predict Observed
Creep Behavior of Leached Salt Caverns

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ABSTRACT

An increasing interest is being shown worldwide in using leached salt caverns to store oil and natural gas. A critical factor in the use of existing caverns and the design of new ones is the creep behavior of the salt surrounding the caverns. An understanding of this behavior is being gained by using laboratory triaxial creep data as material property input to finite element computer programs designed to calculate displacements and stresses due to creep.

An important step in verifying these predictive methods is the comparison of field data from existing caverns with finite element analyses which incorporate the material properties and geometry of each site. This comparison has been made for caverns in the Eminence Dome (Mississippi), West Hackberry Dome (Louisiana), and Bayou Chocktaw Dome (Louisiana) with reasonably good correlation being obtained between measured and predicted volumetric response of the caverns. These comparisons are discussed in this paper.

Introduction

The Strategic Petroleum Reserves (SPR) is a national program dedicated to storage of large quantities of crude oil in leached salt caverns in the Texas-Louisiana gulf coast area. The program has required storage in existing caverns at each site and includes plans to leach new ones. The structural stability of each cavern depends on the behavior of the surrounding salt. In the past cavern stability has been predicted based on experience with other caverns in the vicinity. With the development of good non-linear finite element structural computer programs, it is possible to predict stability before the cavern is created.

An important step in verifying the applicability of these predictive methods is comparison of analytical and field data. The analytical data come from finite element analysis of a specific cavern where the laboratory determined material properties and an approximation to the cavern geometry are used as input. These comparisons have been made for caverns in the Bayou Choctaw Dome (Louisiana), Eminence Dome (Mississippi) and West Hackberry Done (Louisiana) (see Figure 1) with reasonably good correlation being obtained between measured and predicted volumetric response of the caverns.

This paper discusses 1) the acquisition of material properties, 2) the theory behind the finite element creep

program SANCH0, and 3) the comparison of analytical and field data for each of the existing caverns.

Laboratory Triaxial Creep Testing

The creep response of rock salt is usually somewhat site specific even though similarities have been shown to exist among test samples from many locations in the United States (1)(21). Because material differences are possible, salt samples should be obtained from each site and tested for elastic properties and creep characteristics. The elastic properties are obtained using standard triaxial test procedures and the creep characteristics are obtained using two specially constructed triaxial test machines, one of which is shown in Figure 2. These machines were designed for long term (3 months to 1 year) creep testing of cylindrical rock samples. The radial pressure on the specimen is maintained by silicone fluid and the axial stress is generated by a cylindrical ram which acts parallel to the specimen axis. The pressure in the fluid and the ram load must be maintained within certain tolerances over long periods of time. This is accomplished by an incrementally servo-controlled pressure intensifier acting in conjunction with a pump and large gas-filled accumulators(2).

The data obtained from each test are recorded on magnetic tape for later computer processing. This processing involves fitting the data from many tests to a number of different

functions (power, exponential, logarithmic, etc.). The derivatives of these functions are used to fit a creep model which relates effective secondary creep strain rate to effective stress(3):

$$\dot{\epsilon}_s = A \sigma^n \quad [1]$$

where

$\dot{\epsilon}_s$ = effective secondary creep strain rate

A = constant for a given temperature

σ = effective stress

n = stress exponent

The stress exponent "n" is the slope of a line on the log-log plot of effective stress versus secondary creep strain rate. Each point on the plot represents one test and the line is the best fit through many different points. The constant "A" varies with the temperature of the media. For our purposes it was chosen to correspond with the average temperature of each modeled cavern.

The three caverns analyzed in this report were each in a different salt dome. Creep data were available from only one of these sites, West Hackberry, so a decision was made to use the West Hackberry creep data in all three analyses(4). The appropriateness of this decision was supported by the observation of Herrmann, Lauson and Wawersik that salt from three different domes as well as bedded salt from Lyons, Kansas and southeastern New Mexico exhibited similar creep characteristics(1). The three caverns were also at different depths which implied

a different temperature range for each cavern and necessitated using a different value of "A" in each analysis.

Finite Element Analysis

SANCHO is a developmental structural finite element code which was derived from HONDO II⁽¹⁶⁾. SANCHO has most of the important features associated with HONDO II such as large strain, large deformation, and a large selection of constitutive models. Dynamic relaxation is used to find static solutions at user specified time steps. A dynamic relaxation solution involves adding an acceleration term to the equilibrium equation, which converts a static problem into a dynamic one involving a psuedo-time measure. An internally computed "optimum" damping value is used to follow the "transient" response out in psuedo-time until a converged static solution is obtained. Convergence of this iterative procedure is based on the satisfaction of global equilibrium at a given load step. The magnitude of the residual force vector is compared to the magnitude of the applied load vector to determine when global equilibrium has been reached.

The creeping material model is currently restricted to secondary creep expressed in a power law form. The integration of the model is done "semi-analytically" and has been shown in tests to be quite accurate. There are no stability or time step restrictions as usually associated

Volumetric Measurements and Computations

Since rock salt is a geologic media the properties may vary from point to point in a dome. Because of this, it was decided that correlation between field data and finite element analyses would be more meaningful on a volumetric basis since the integrated nature of the volumetric response (decrease in cavern volume due to creep closure) tends to reflect an average of material properties. Volumetric response was also more easily obtained in the field because flow rate and pressure could be measured at the wellhead whereas creep displacement measurements would have to be made underground. The volumetric response of each of the three caverns discussed in this report was obtained in different ways and will be discussed later.

Time steps are used to do the finite element creep calculations. At the end of each time step the program stores the displacements corresponding to each node and the stresses corresponding to each element. An algorithm has been employed to calculate the area and centroid of the two-dimensional axisymmetric cavern model from the displaced coordinates. The algorithm employs the following equations(5):

$$A = - \sum_{i=0}^n (Z_{i+1} - Z_i) (R_{i+1} + R_i) / 2 \quad [2]$$

$$\bar{X} = \frac{1}{A} \sum_{i=0}^n [(Z_{i+1} - Z_i) / 8] [(R_{i+1} + R_i)^2 + (R_{i+1} - R_i)^2 / 3] \quad [3]$$



with classical Euler integration involved with this method. The only consideration is that the strain rate is constant within the time interval that accuracy of the solution is the dominant concern(17).

SANCHO was a participant in the recent WIPP (Waste Isolation Pilot Plant) Benchmark II exercise where a generic waste isolation drift in bedded salt was analyzed(18). SANCHO results compared very well with results from the eight other structural codes which were exercised in the benchmark study.

where

A = area (of two-dimensional model)

\bar{R} = radial coordinate of centroid

R_i, Z_i = nodal coordinates around cavern boundary

n = number of nodes around cavern boundary

The displacements at the end of each time step are added to the coordinates of the nodes surrounding the cavern. The displaced coordinates of the nodes surrounding the cavern are then used in equations [2] and [3] to obtain the area and centroid of the cavern model. Since the analysis is axisymmetric the volume can be obtained by

$$V = 2 \pi \bar{R} A \quad \text{L-41}$$

In this manner the volume of the cavern can be calculated at each time step. The volume-time data can then be manipulated to give flow rates and pressure increases as functions of time.

Bayou Choctaw Cavern Number 2

The Bayou Choctaw salt dome is located in south-central Louisiana approximately 13 miles southwest of Baton Rouge. The dome was discovered in 1926 and its flanks were extensively explored for oil. Allied Chemical Corporation purchased a portion of the middle of the dome and began drilling brine wells in 1934. Figure 3 shows the location of the caverns created by brining operations.

Cavern Number 2 was drilled to a depth of 1846 ft. in 1934. Brine production eventually produced the 9.02 million barrel cavern shown in Figure 4. Brine production was stopped when it was determined that only a thin web of salt was left between the top of the cavern and the caprock. Loss of salt in the roofs of other caverns had resulted in cavern collapse. The United States Department of Energy (DOE) purchased the cavern in 1976 along with others in the dome. This cavern was judged unsuitable for oil storage because of the thin roof salt and has been used recently as a test cavern⁽⁶⁾.

The wellhead of this cavern is typically sealed for several months at a time with the pressure gradually building due to creep closure of the cavern. When the pressure reaches approximately 100 psi, the wellhead is opened and brine allowed to flow until the pressure has been significantly reduced. It is possible to accurately convert pressure changes at the sealed wellhead to volume changes due to creep. The necessary relationship can be obtained by

observing the pressure change when a measured amount of fluid is pumped into or out of the cavern. Sandia personnel determined this relationship for cavern 2 to be 30.5 barrels of brine per psi.

The steady state pressure increase at the wellhead was measured over about a month to be 0.177 psi per day. This corresponds to a rate of volume change in the cavern of 30.27 cubic feet per day.

A physical phenomenon which must be taken into account when measuring wellhead pressures is the pressure change due to thermal expansion of the fluid. Usually the fluid pumped into the cavern is at a lower temperature than the surrounding media and gradually expands as it is heated. Observations in France of similar sized caverns showed that they usually reached thermal equilibrium in about twelve years⁽¹⁴⁾. Since brining operations stopped on Bayou Choctaw Number 2 over twenty years ago it is felt that this cavern is in thermal equilibrium with its surroundings and does not exhibit pressure increase due to thermal expansion.

The axisymmetric finite element approximation of this cavern is shown in Figure 5. The cavern model has a volume of 9.025 million barrels, a height of 800 feet and a radius of 142 feet (chosen to give the measured sonar volume). The boundary conditions include geostatic pressure across the top of the mesh and pressure inside the cavern corresponding to brine head from the ground surface. The boundary conditions

on the right and left sides of the mesh allowed vertical displacement but no horizontal displacement. On the bottom of the mesh the horizontal displacements are free and the vertical are fixed. All of the caverns surrounding cavern 2 are at approximately the same depth except cavern 15, whose top is well below the bottom of cavern 2. As can be seen in Figure 3 there are no other caverns in a northeastern direction from cavern 2. Because of this the pillar distance required to simulate an infinite boundary was included in the average of pillar distances used to obtain the width of the mesh. The pillar distance required to simulate an infinite boundary was determined to be eight times the cavern radius by analyzing a generic cavern with successively wider meshes until minimal change in stress was observed on the right boundary at 30 years.

As mentioned previously the pressure in the cavern is allowed to build to around 100 psi before bleed-down occurs. These pressure increases over time were not included in the finite element model because they constituted less than 10 per cent of the brinehead pressure existing in the cavern.

The salt properties used were from the West Hackberry Dome since those data were available at the time of the analysis⁽⁴⁾. These properties were compared with elastic coefficients measured at Bayou Choctaw and found to be in close agreement. The "A" coefficient was determined using a temperature at the mid-height of the cavern of 41°C. This was estimated from borehole temperature logs. The elastic

properties of the shale in the caprock were taken from previous analyses involving shale layers⁽²⁰⁾. The material properties chosen were:

Shale

Young's Modulus = 1.48×10^8 psf

Poisson's Ratio = 0.29

Salt

Young's Modulus = 4.61×10^8 psf

Poisson's Ratio = 0.26

Coefficients for equation [1]

stress exponent $n = 4.9$

A (corresponding to 41°C) = 9.02×10^{-31}

(psf and days)

The volumetric response of the cavern obtained from the finite element model is plotted as a function of time in Figure 6. There is some transient behavior evident on the plots since the rate of change of the total volume is gradually decreasing. The flow rate computed at 3000 days where the transient behavior has diminished is about 22 cubic feet per day. Comparing this with the measured flow rate of 30 cubic feet per day indicates that reasonably good correlation (for field events of this size and uncertainty) between field and calculated data has been obtained.

Eminence Cavern Number 1

The Eminence salt dome is located in south central Mississippi about 20 miles north of Hattiesburg. The dome was discovered in 1947 but has never been used for oil or gas production(B). In 1970 Transcontinental Gas Pipe Line Corporation (TRANSCO) completed the first of four natural gas storage caverns⁽⁹⁾. The geometrical description of this cavern is shown in Figure 7. This is an interesting cavern to test the predictive methods on because: 1) it is very deep in comparison with Bayou Choctaw Number 2 providing an indication of the range over which calculations are valid, 2) it has relatively simple geometry making creation of a finite element mesh easy, 3) good data were available from TRANSCO on the volumetric response of the cavern with time, and 4) the large difference between internal pressure and geostatic stress caused rapid closure of the cavern.

In May 1970 the brine was removed from the cavern and replaced with natural gas. These caverns were dry-type (brine-free) meaning that the natural gas was stored under pressure and removed by free-flow rather than being displaced by inserting brine into the cavern. However, when all the gas was removed from a cavern it was filled with brine.

The initial volume of each cavern was determined using the volume of fresh leaching water and the salinity of the returning brine. Sonar and metering of input and output volumes of brine or fresh water were used to make subsequent measurements of cavern volume. The natural gas storage pressure

in the cavern varied between a maximum of 3860 psi and a minimum of 1300 psi. A time weighted average of internal cavern pressure taken from TRANSCO data⁽¹¹⁾ was 3000 psi. This value was used in the analysis.

The axisymmetric finite element model of this cavern is shown in Figure 8. The finite element model has a cavern volume of 1.0788 million barrels compared to a volume measured from leach and sonar data to be approximately 1.1008 million barrels. The mesh is made up of four node quadrilateral SANCHO elements with geostatic pressure across the top and a constant pressure of 3000 psi inside the cavern. Boundary conditions similar to the Bayou Choctaw 2 model were placed on the right and left sides and along the bottom of the mesh.

The temperature of the salt around the cavern was taken to be 60°C from a Bayou Choctaw temperature log⁽⁶⁾. This temperature was used in the selection of the creep coefficient "A" in equation [1]. The width of the pillar between caverns was not available from TRANSCO. However, judging from the fact that there are only four caverns total in Eminence dome and the dome width is approximately one mile in diameter⁽¹⁶⁾, a spacing of 600 feet was chosen with a pillar of 420 feet. Previous calculations had shown that widening the mesh any farther did not change the results significantly.

The salt properties were approximated entirely with the West Hackberry properties since Eminence is not an SPR site and material property data were not available⁽⁴⁾. The

material properties were:

$$\text{Young's Modulus} = 4.61 \times 10^8 \text{ psf}$$

$$\text{Poisson's Ratio} = .263$$

Coefficients for equation [1]

$$\text{stress component } n = 4.9$$

$$"A" \text{ (corresponding to } 60^\circ\text{C)} = 1.769 \times 10^{-30} \text{ (psf and days)}$$

The computed volumetric response of cavern 1 and the measured response are plotted against time in Figure 9(10). The analysis was performed at two different internal pressures, 2000 psi and 3000 psi, to give an indication of pressure sensitivity. The response of the cavern corresponding to the average geostatic pressure inside the cavern (about 6000 psi) would be roughly a horizontal line since virtually no volume change would take place. It can be seen from Figure 9 that the computed response tracks the measured response quite closely.

Because of severe creep closure the caverns at Eminence were termed a failure by some(10) though the caverns were never structurally unstable and did not collapse. It appears that this large closure rate was the result of the caverns being too deep where high temperature and large stress differences accelerated the creep closure of the caverns.

West Hackberry Cavern Number 11

The West Hackberry salt dome is located in Southwestern Louisiana approximately 20 miles southwest of lake Charles. The dome was discovered in 1901 and initially explored extensively for oil. In 1934 Olin Corporation began producing brine from solution mined caverns. One of these, Number 11, was purchased by DOE along with four others in 1977.

Leaching was begun on cavern 11 in 1962 and continued almost constantly until DOE obtained the cavern. This cavern is a good test cavern because 1) it is similar in size, shape and depth to the new SPR expansion caverns, 2) it is relatively far from other caverns in the dome which makes interaction unlikely, and 3) it is presently full of oil. This 8.5 million barrel cavern is shown in Figure 10(12).

The operation of this cavern is similar to that of Bayou Choctaw number 2 discussed earlier. The pressure is allowed to build to approximately 100 psi at which time brine is bled from the bottom of the cavern to relieve pressure. There is a significant amount of wellhead pressure data currently available but the flow on bleeddown has not been measured to give a physical correlation between wellhead pressure increase and volume change. Because of this the calculated volume change of cavern 11 had to be converted mathematically to a pressure change. The volumes, compressibilities and densities of the oil and brine are known within reasonable accuracy. These values are used in the equations relating

fluid density to compressibility and pressure to develop an equation relating total volume to total pressure in the cavern(13). This equation was programmed and added to the end of the volume calculation program.

The wellhead pressure data were somewhat crude, being read manually every day from gauges mounted on the wellhead. These readings were entered into a computer for statistical processing so that the scatter introduced by lack of gauge calibration and human error could be minimized by looking at data spanning many months. Enough of these data were gathered and processed to give some confidence in the results. Table 1 contains a summary of the data obtained. In Table 1 "fluid side" indicates whether the pressure measurement was taken on the brine pipe or oil pipe going into the well.

Table 1

<u>Dates</u>	<u>Fluid Side</u>	<u>Pressure increase(psi/day)</u>
May 80 to Jan 81	Oil	1.6
May 80 to Sept 80		1.8
Oct 80 to Jan 80	"	1.0
May 80 to Aug 80	Brine	1.6
Oct 80 to Jan 81	"	1.3
Jan 81 to Apr 81	"	1.1

Mean = 1.4 psi/day

Standard Devlation = .32 psi/day

Part of the pressure increase recorded in Table 1 is due to creep closure of the cavern and part is due to thermal expansion of the oil as it heats to equilibrium⁽¹⁴⁾. A thermal analysis has been made of West Hackberry Number 6 which is a 12.2 million barrel pancake shaped cavern at approximately the same depth as cavern 11. This analysis predicted a pressure increase due to thermal expansion of the oil to be between 0.09 and 0.18 psi per day⁽¹⁵⁾. It is believed that the thermal behavior of cavern 11 would be similar to cavern 6 since the two have approximately the same volume and reside at the same depth. Using this assumption and the standard deviation from Table 1 a pressure increase somewhere between 0.90 and 1.63 psi per day can be attributed to creep closure.

The axisymmetric finite element mesh of cavern 11 is shown in Figure 11. This model has a cavern volume of 8.52 million barrels, a height of 800 ft. and a radius of 138 feet (chosen to give measured sonar volume). The boundary conditions are similar to Bayou Choctaw No. 2. The pillar was made wide enough to simulate an infinite boundary since the nearest cavern is over 2000 feet away.

The temperature of the salt surrounding the cavern is not accurately known. It should be less than the original temperature because relatively cool fresh water and oil have been pumped into the cavern for 19 years. Because of this uncertainty two analyses of the cavern have been performed, one at 47°C which is the estimate original temperature and

one at 22°C which is the estimated temperature of fluids pumped into the cavern.

The material properties chosen using West Hackberry test data were⁽⁴⁾:

$$\text{Young's Modulus} = 4.61 \times 10^8 \text{ psf}$$

$$\text{Poisson's Ratio} = 0.26$$

Coefficients for equation [1]

$$\text{Stress exponent } n = 4.9$$

$$A \text{ (corresponding to } 22^\circ\text{C)} = 2.54 \times 10^{-31} \text{ (psf and days)}$$

$$A \text{ (corresponding to } 47^\circ\text{C)} = 1.10 \times 10^{-30} \text{ (psf and days)}$$

The pressure increase calculated for the two different temperatures is given in Table 2.

Table 2

<u>Analysis Temperature (°C)</u>	<u>Predicted pressure increase(psi/day)</u>
22	0.75
47	3.00

The measured value range of 0.90 to 1.63 psi per day falls within the range of values in Table 2 and indicates reasonable correlation.

Concl usi ons

The use of material properties from triaxial creep tests in finite element analysis provides a reasonably reliable method for predicting the volumetric response of salt caverns due to creep. The material testing procedures and the analytical approach used here have been shown to be valid by comparison of analytical results with flow rate and pressure data obtained in the field. The three caverns analyzed provide enough variety of loading conditions geometrical shapes and sizes to indicate that the analytical methods are quite generally applicable. These methods will be used in the future to predict the response of new and existing caverns which will be employed in the SPR program.

Acknowledgements

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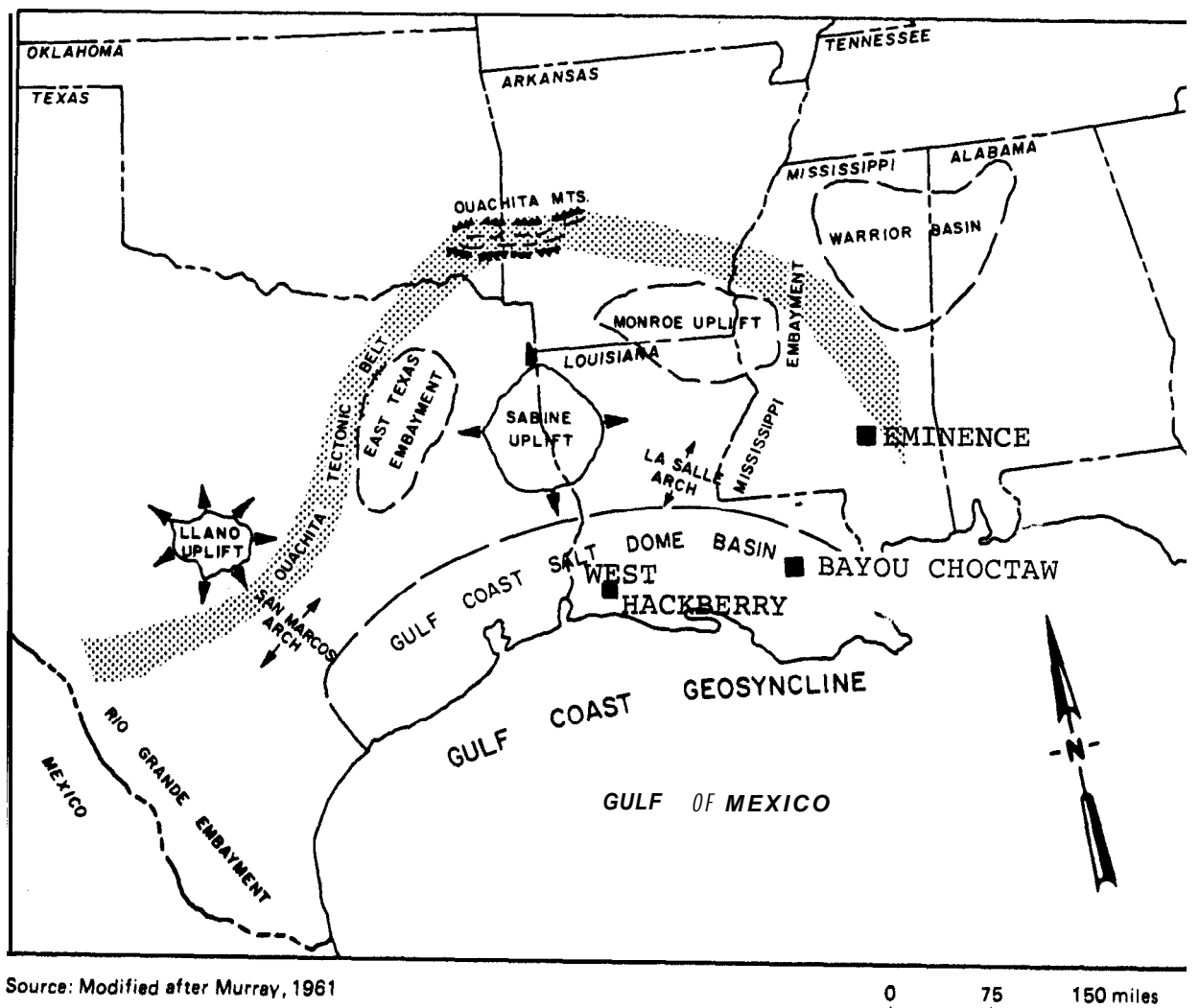


Figure 1
Geographical Location of Bayou Choctaw, Eminence
and West Hackberry Salt Domes

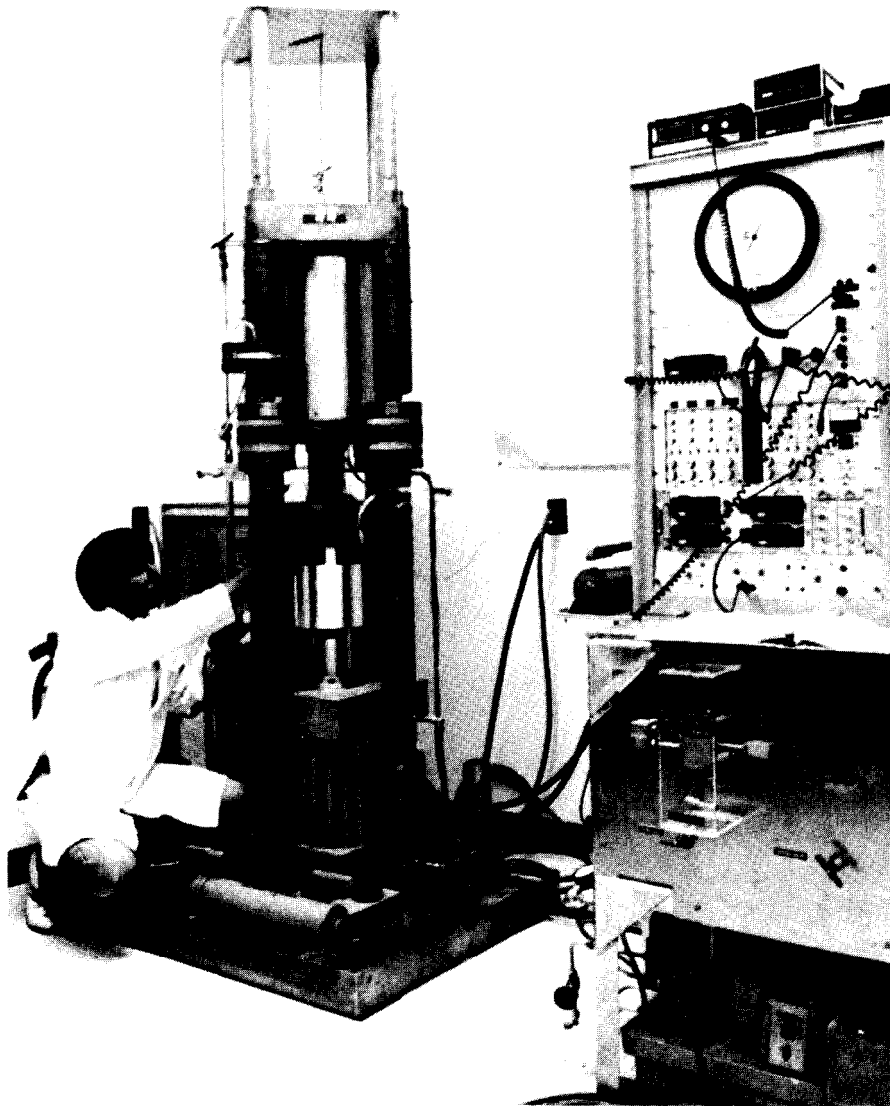


Figure 2. Tri axial Creep Testing Apparatus

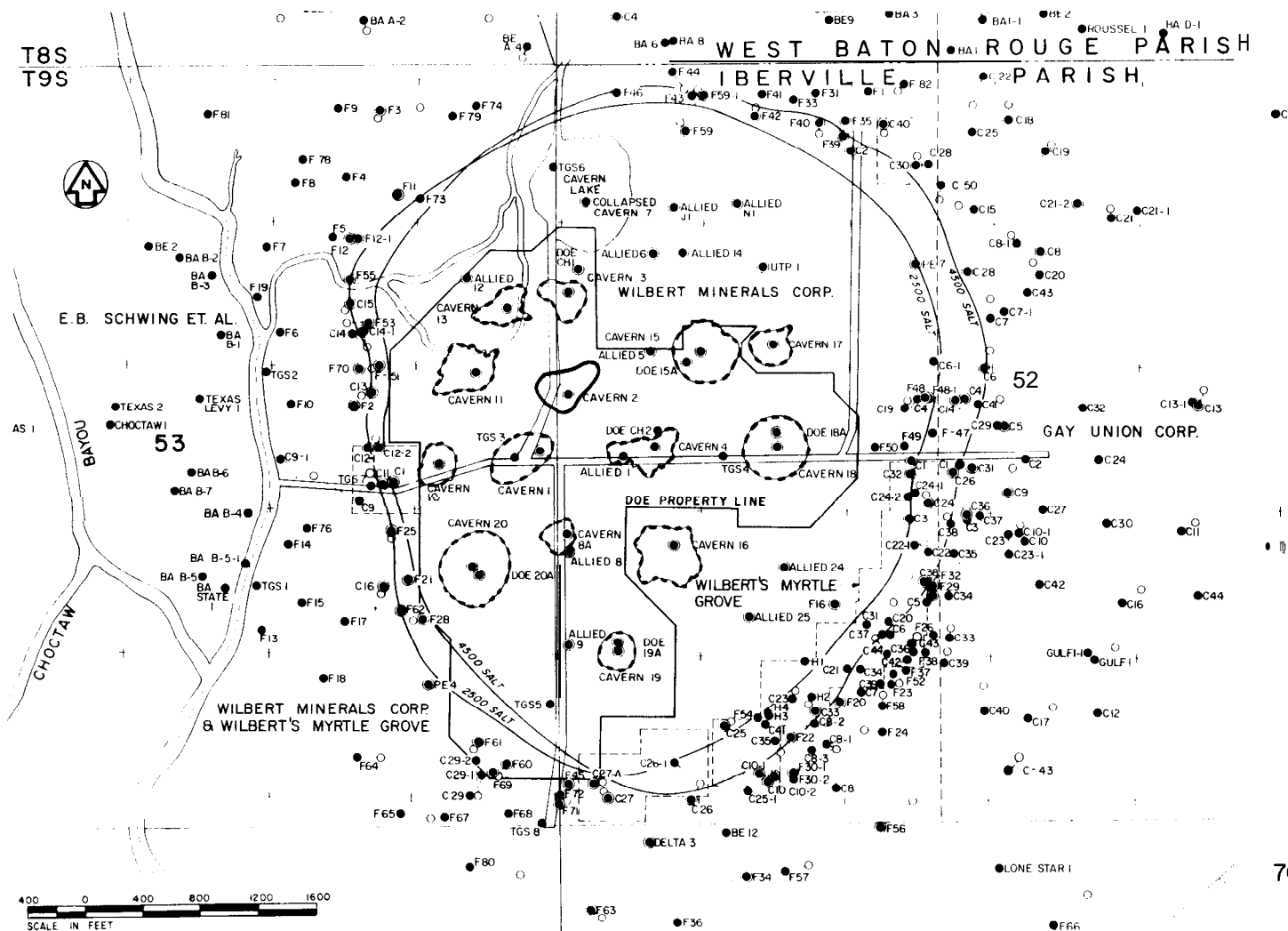


Figure 3
Existing Caverns at Bayou Choctaw Dome

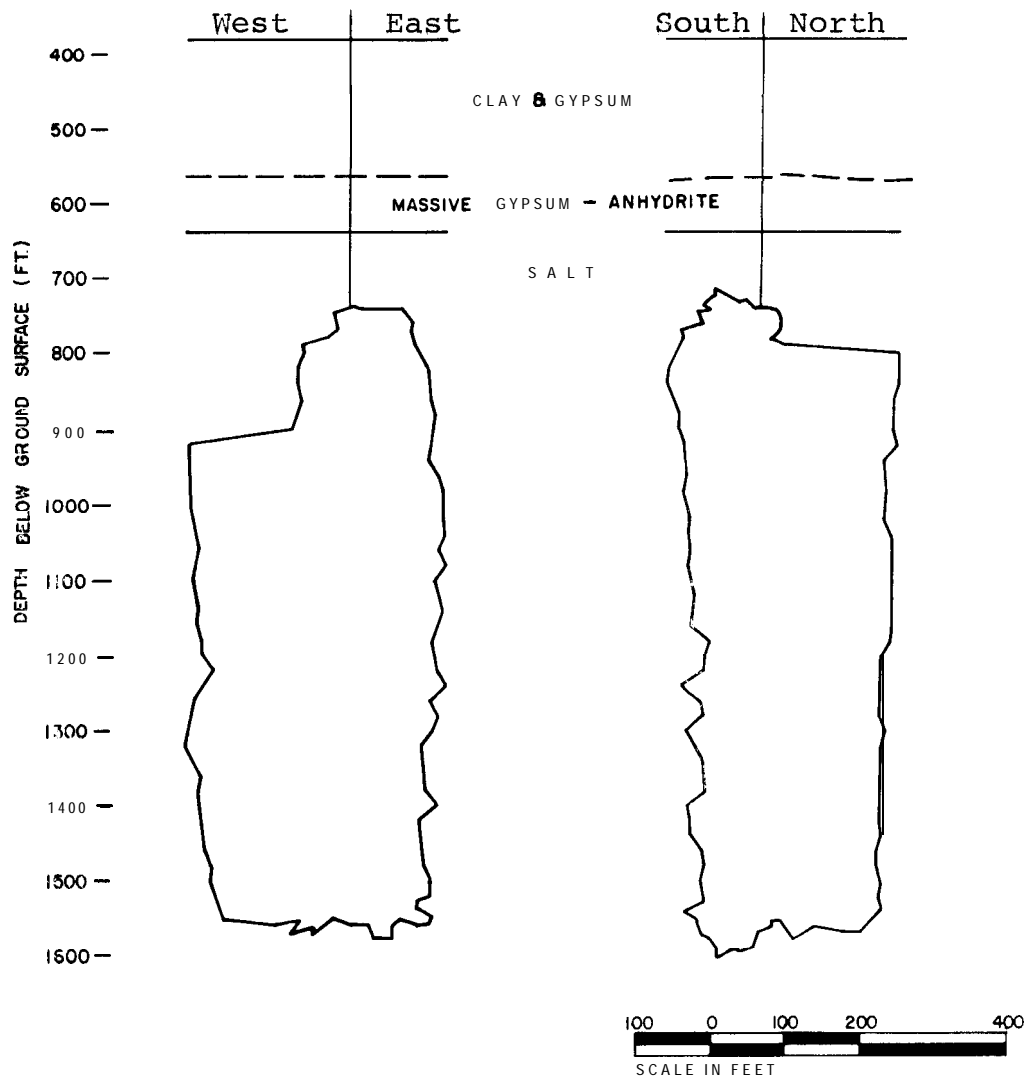


Figure 4
Geometry of Bayou Choctaw Cavern Number 2

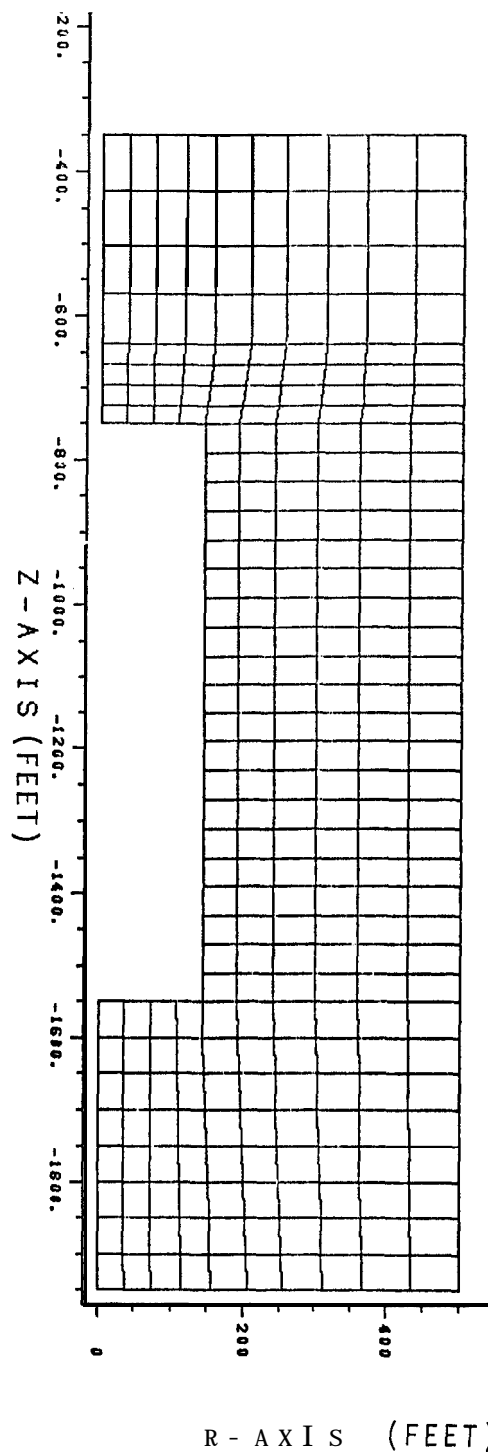
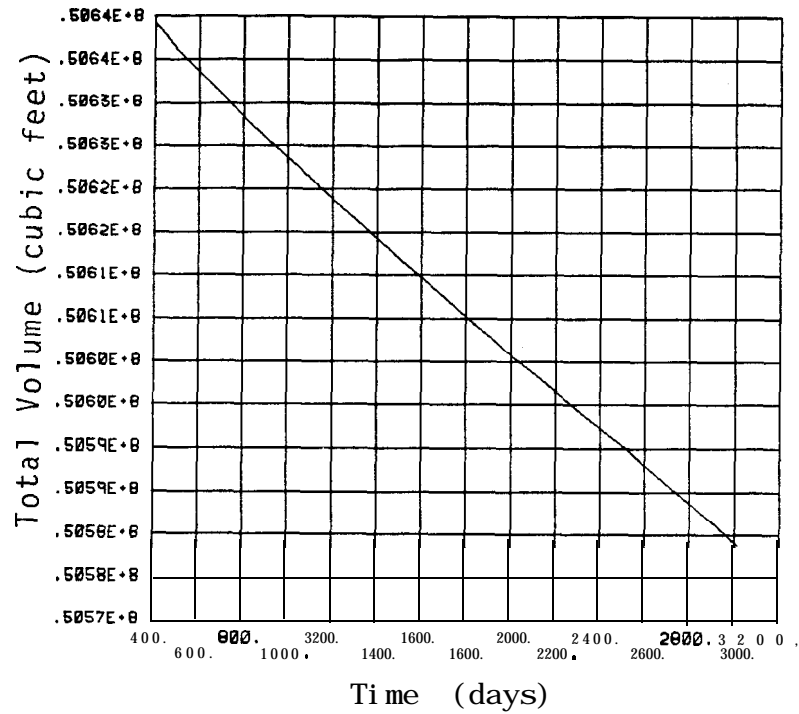
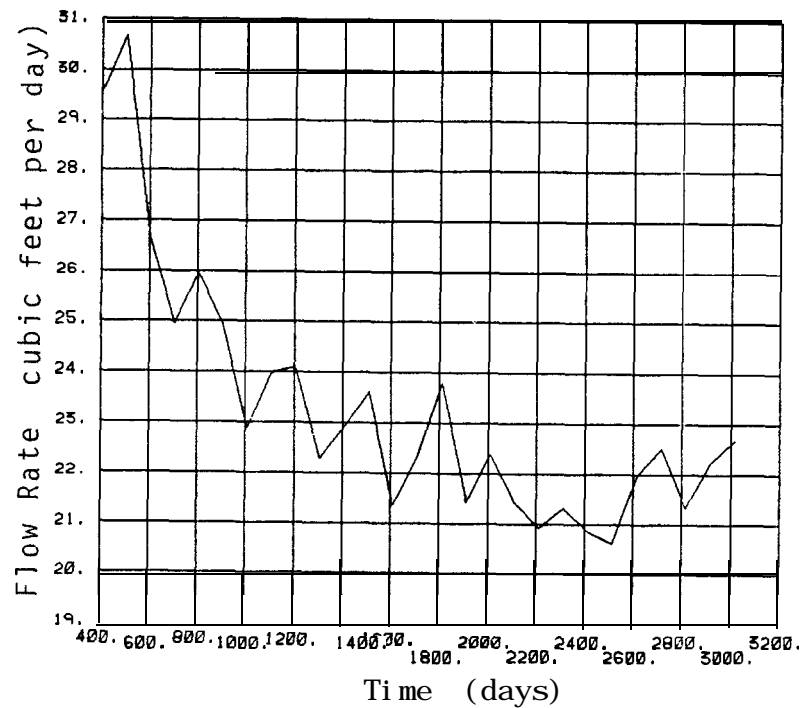


Figure 5
Finite Element Model of Bayou Choctaw Cavern 2



a. Total Volume versus time



b. Flow rate versus time

Figure 6

Volumetric Response of Bayou Choctaw Cavern 2

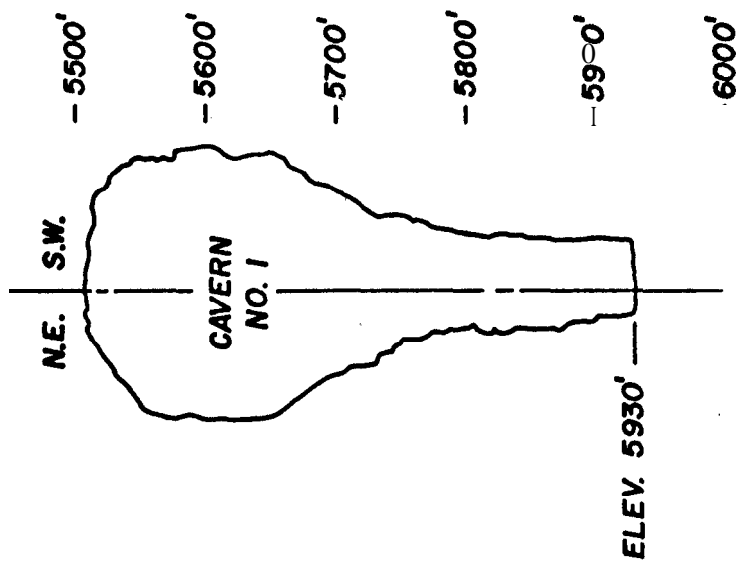


Figure 7
Geometry of Eminence Cavern Number 1

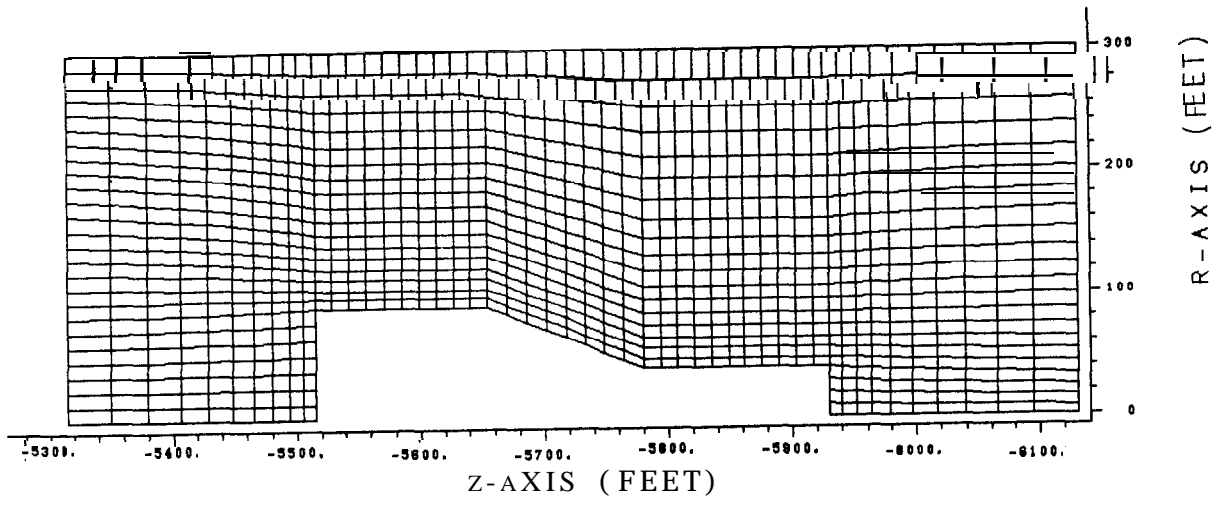


Figure 8
Finite Element Model of
Eminence Cavern Number 1

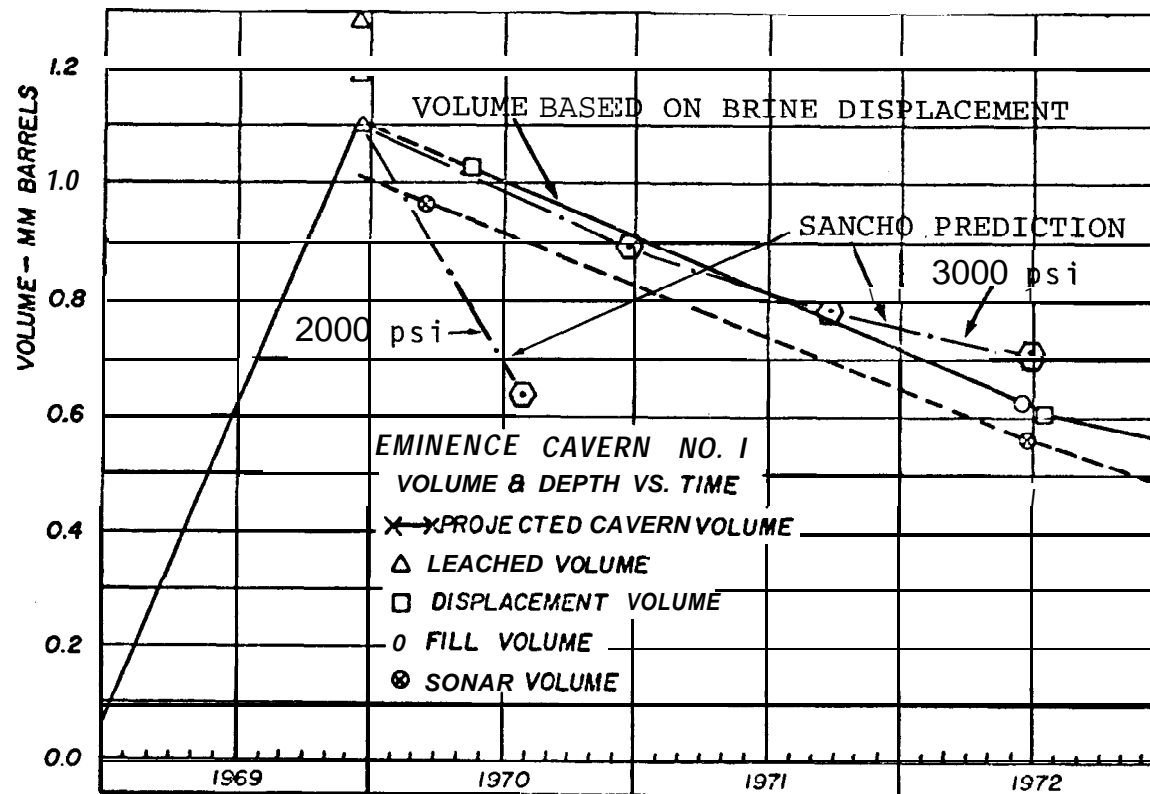


Figure 9
Total Volume Versus Time
(After Fenix & Scisson, 1975)

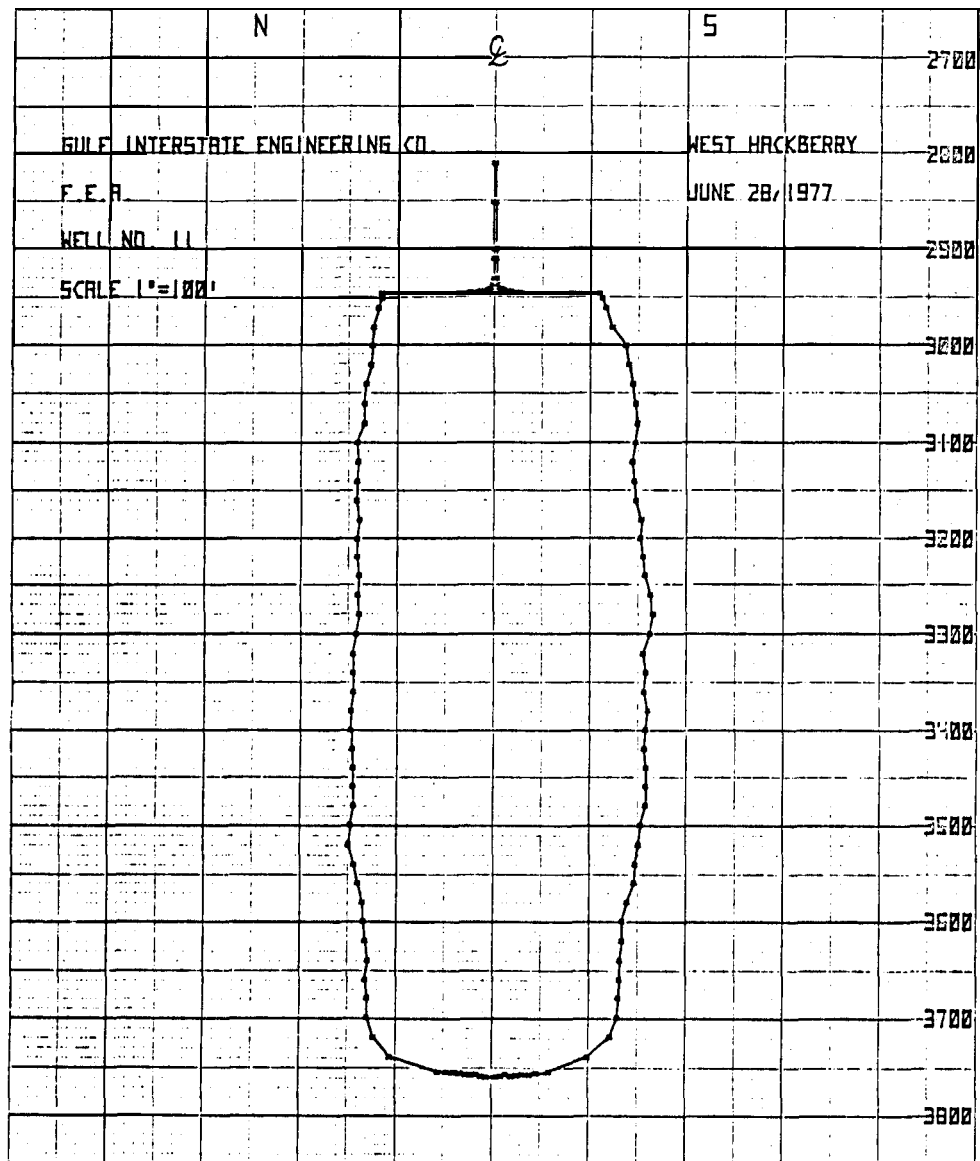


Figure 10
Geometry of West Hackberry Number 11

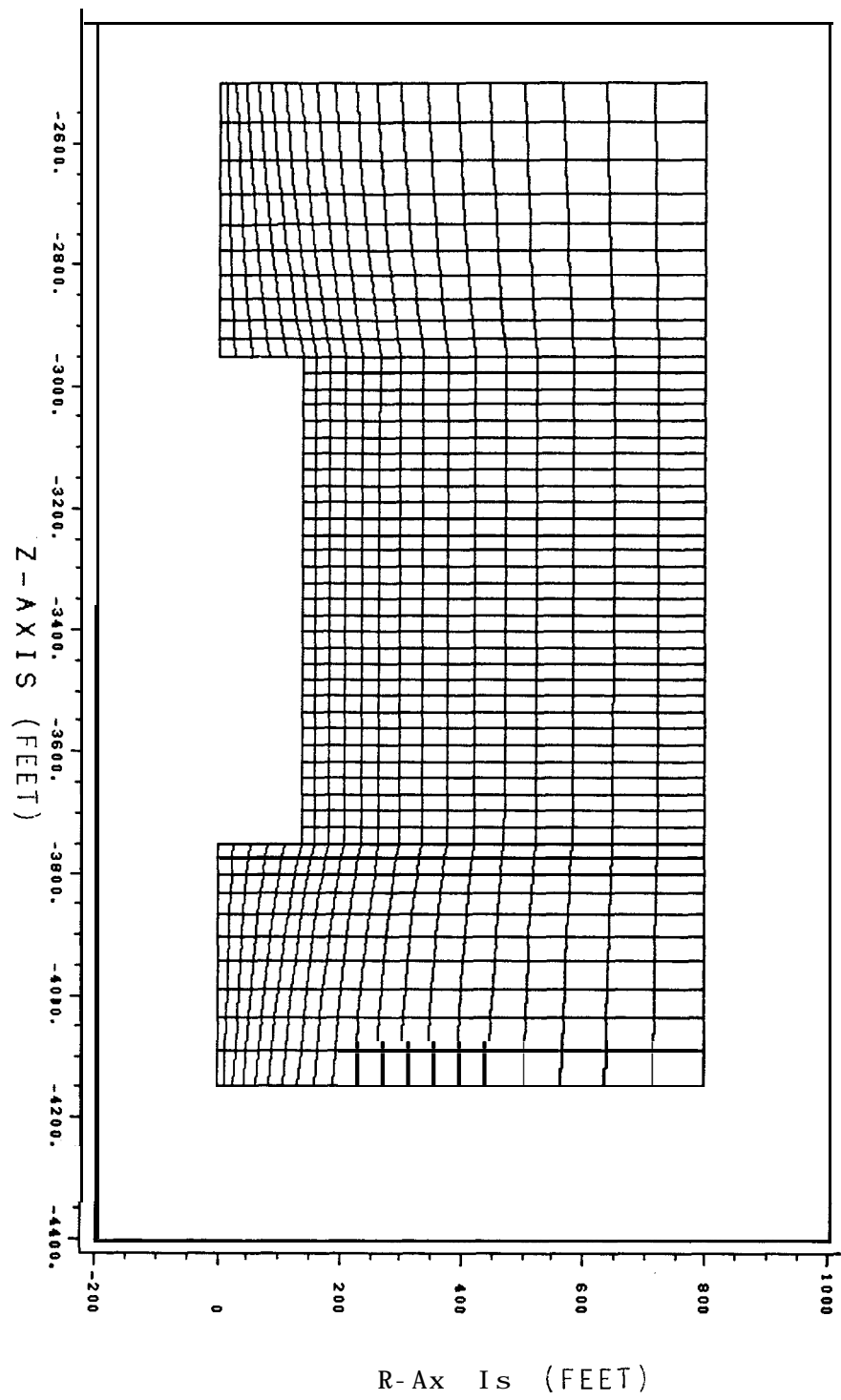


Figure 11
Finite Element Model of West Hackberry Number 11

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1520 T. B. Lane
1521 R. D. Krieg
1521 C. M. Stone
1522 T. G. Priddy
1522 D. S. Preece (10)
1530 W. Herrmann, Actg
1531 B. J. Thorne
1532 B. M. Butcher
1800 J. K. Galt, Actg
1820 R. E. Whan
Attn: 5812 N. E. Brown
7000 O. E. Jones
7100 C. D. Broyles
7120 T. L. Pace
7125 G. L. Ogle
9000 G. A. Fowler
9200 W. C. Myre
Attn: 9260 J. Jacobs
9269 J. D. Williams
9700 E. H. Beckner
9760 R. W. Lynch
Attn: 9761 L. W. Scully
9770 G. E. Brandvold
Attn: 9772 J. W. McKiernan
9773 J. F. Ney (10)